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Laboratory Feasibility Study Concerning the Use of the SediMeter™ to Detect Fine-Scale (≤ 1 mm) Sedimentation Resulting from Dredging Operations

by David W. Perkey and Heidi M. Wadman

INTRODUCTION: The United States Army Corps of Engineers (USACE) is responsible for the operation and maintenance of much of the nation's inland waterways. USACE currently maintains 12,000 miles of commercial and navigation channels, 926 harbors, and owns and operates more than 600 dams. In the process of managing these resources, USACE dredges more than 200 million cubic yards of material annually (USACE headquarters services, http://www.usace.army.mil/Services/Pages/Services.aspx). As a result of this dredging activity, bottom sediments are stirred up and resuspended into plumes. The transport of these plumes via currents can have physical, biological, and chemical impacts on habitats downstream of dredge sites (e.g., Wildish and Thomas 1985; Wilber and Clarke 2001; Hossain et al. 2004; Nayar et al. 2007). In some sensitive habitats, it has been suggested that increased sedimentation on the order of 1mm or less can result in harmful impacts to the environment. Consequently, dredging operations are often regulated and dredging windows are put into place to reduce the effects of this assumed sedimentation. Currently, there is no accepted method to quantify sedimentation resulting from dredge-induced suspensions, making it difficult to determine the impacts of this sedimentation on a habitat.

Recently, new instrumentation has been developed that may have the ability to quantify sedimentation on the scale of 1mm or less; however, these instruments require laboratory and field testing to demonstrate their ability to accurately measure fine-grained sedimentation at the sub-millimeter scale. As part of the Dredging Operations and Environmental Research (DOER) Program, researchers at the USACE Engineering Research and Development Center-Coastal and Hydraulics Laboratory (ERDC-CHL) are currently testing and evaluating some of these technologies. One such instrument is the SediMeter™, designed by Lindorm, Inc. SediMeter™ utilizes infrared optical backscatter (OBS) detectors to determine bottom location. This report will present the results of a series of laboratory tests that were conducted to determine the instrument's measuring accuracy and assess its capacity for monitoring fine-scale sedimentation resulting from dredging operations.

Materials and Methods

SediMeter™. The SediMeter™ (Figure 1) is composed of a computer and sensor that utilize infrared OBS detectors to determine the location of the bottom. An array of 36 OBS detectors, spaced 1cm apart, measures a turbidity profile. A bottom level is then interpolated from the turbidity profile. As illustrated in Figure 2, the instrument is designed to be deployed, first, by hand-augering a clear plastic tube into the substrate. The SediMeter™ probe containing the detectors is then slid into the plastic tube and secured in place with a set screw. The sampling

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protocol is programmed by the user into the attached LogDator™ computer, and resulting data is stored on the computer (2MB flash) or on SD/MMC memory cards.

Figure 1. Picture of the SediMeter™ (right) with the sampling tube (left) and auger system (middle). OBS detectors are contained within the green section on the instrument.

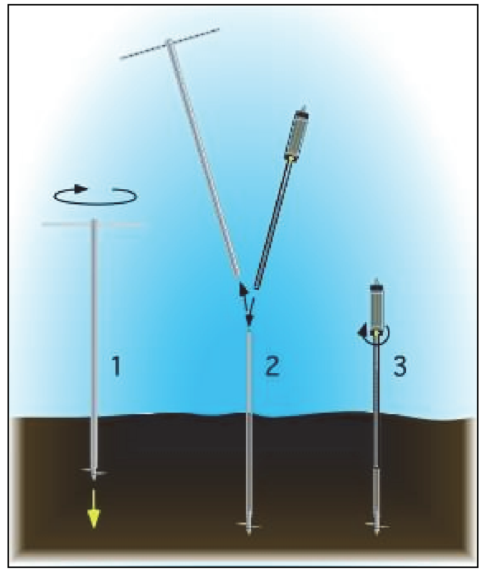

Figure 2. Illustration of the SediMeter™ being deployed. 1) Plastic sampling tube is screwed into bottom. 2) Auger handle removed and SediMeter™ is inserted into tube. 3) Set screw is tightened down to hold SediMeter™ in tube.

Experimental Design. To determine the accuracy of the bed-level-elevation measurements, three SediMeters™ were tested. The SediMeters™ were mounted vertically to a Sigma Koki Co. SGSP26-100 linear actuator (Figure 3). To allow for automated motion control, the actuator was interfaced to a laptop computer. The SGSP26-100 is capable of moving at increments less than 3µm, and has a total travel distance of 100mm. The SediMeter™ was inserted into its plastic sampling tube, which was centered in a 7.6cm diameter clear plastic barrel fitted with a water tight cap on one end. The barrel was filled with wet, medium-coarse sized sand (D_{50}= 470.03µm) to an elevation 15cm below the top, making sure that the SediMeter™ tube stayed centered within the barrel during the filling process. The remaining space in the barrel was then filled with water. To allow for free vertical motion of the SediMeter™ within the plastic sampling tube, the set screw was not tightened as illustrated in step three of Figure 2.

Once positioned, the SediMeters™ were programmed using the control software and allowed to acquire data while stationary in the sampling tube. After allowing an initial bed-level reading to be taken, the SediMeters™ were repositioned by moving the linear actuator up or down. The time, magnitude, and direction of motion were recorded each time the SediMeter™ was repositioned. To document motion steps made with the actuator, a digital camera attached to a stationary tripod was used to take photos of the actuator's position after each motion step. A tape measure with a 1mm

Figure 3. Picture of the SediMeter™ mounted to the linear actuator. The SediMeter™ is placed within the plastic sampling tube, and approximately half of the detectors are below the sand surface in this photo.

scale was secured adjacent to the actuator and was used to make visual verification of that motion (Figure 4). Photograph numbers were also recorded with each motion step and were reviewed to confirm the magnitude of movements made by the actuator. Multiple tests were performed in this manner with each of the three SediMeters™, with varying changes in sampling durations and motion steps. The magnitude of each motion step ranged from 0-15mm, but in most instances steps were either 1mm or 10 mm.

At the end of each test, the data were recovered from the memory card and processed using SediMeter™ software 2.3.2. The bed levels resulting from the interpolation of the turbidity profile were used to calculate the magnitude of motion the instrument measured at each step. This was compared to the corresponding motion of the linear actuator. A difference between the two was calculated and compiled for each of the three SediMeters™. These values were averaged and a standard deviation was determined. The empirical rule was then utilized to determine the accuracy of the SediMeter's™ bed-level measurements.

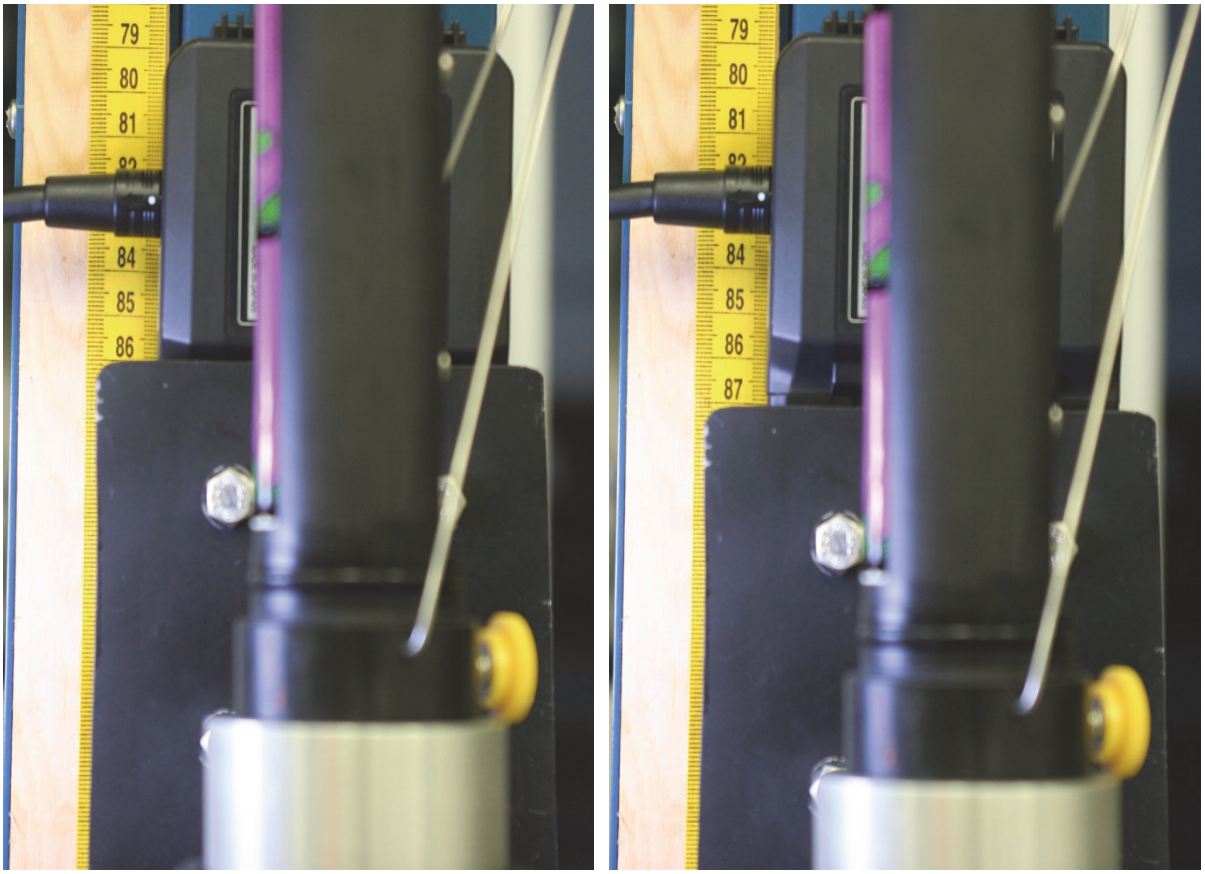

Figure 4. The above photographs show sequential positions of the linear actuator after being moved 1cm down. The tape measure in the background confirms this motion.

RESULTS

Instrument Operation. During the laboratory testing of the SediMeter™, two technical points of concern that impact the general functionality of the instrument were observed. The first issue pertained to the memory cards used to store the data collected by the SediMeter™. After using a memory card for approximately half a dozen to a dozen tests, the SediMeter™ would stop writing data to the card. During the programming and deployment set-up of the SediMeter™, there was no indication of memory card failure. Discovery of the error was only determined after a test had been conducted, but no data had been written to the card. Lindorm, Inc. was contacted about this problem and has apparently determined that the error occurs when the instrument is being used in "Logger" mode. To avoid data recording failure three alternatives were suggested:

1. Store the data to the internal flash memory instead of the memory card.

2. Format the memory card with the SediMeter™ prior to each deployment. Deleting the files on the SD/MMC card on a PC will not solve the problem and the SediMeter™ does not prompt the user to format the memory card before deployment.

3. Program the SediMeter™ to operate in "Master" mode instead of "Logger" mode.

These three alternatives were developed after ERDC-CHL had finished the laboratory testing and therefore have not been attempted or evaluated at the time of this report.

The second issue involves the sensor wiper designed to clean the plastic sampling tube which the SediMeter™ rests in, reducing biofouling. All three of the SediMeters™ that were used in this test were equipped with the wiping system. However, when deployed for the first time, the wiper systems failed and the instruments were unable to properly retract the wipers to their home positions. Lindorm, Inc. discovered an error in the firmware of the instrument which causes this malfunction. To conduct the tests that were discussed above, the wiper systems were removed from all three SediMeters™. At the time of this report, corrections to the firmware of the three SediMeters™ have not been made, so no statement as to the functionality of the wipers can be provided.

Experimental Data. When the SediMeter™ recorded motion was compared to the motion of the linear actuator, a similar pattern was observed for all three SediMeters™. The mean difference between the two measurements of motion was calculated for each individual SediMeter™ and t-tests (α=0.05) showed that there was no significant difference between the means of the three instruments. Because no statistical difference was found between the SediMeters™, the results from all tests were compiled into one data set for analysis.

When evaluating the SediMeters™, the first parameter that was investigated was the stability of the bed-level measurements. It was found that during periods of time when the SediMeters™ were left stationary the reported bed elevations showed little to no variation, as seen in Figure 5. However, while the SediMeter™ measurements were stable and mimicked the pattern of motion of the actuator, the amount of motion that occurred between each step often varied from what was seen on the actuator. These fluctuations are illustrated more clearly by the graph in Figure 6, which shows only the 10 changes in elevation that resulted in the stair-step pattern of Figure 5. In this test, the differences between the recorded motion of the SediMeter™ and the actual movement for each elevation change ranged from -1.3mm to 1.5mm. This sequence of underestimations of bed-level elevation followed by overestimation events resulted in the final bed-level elevation and total motion, as measured by the SediMeter™, being very similar to what was measured on the actuator. However, the accuracy of each individual step in motion was shown to be a potential point of concern.

As stated above, this pattern of discrepancy between the SediMeter™ recorded motion and the motion observed on the actuator was consistent for all three SediMeters™. A test conducted with SediMeter™ #3 (Figure 7) further illustrates this point. In this test, the actuator was moved 89 times in 1mm increments. The SediMeter™ reported an elevation change of 1mm 16 times. The remaining 73 motion steps were nearly equally reported as underestimations (n=38) or overestimations (n=35) of elevation change. The difference between actuator motion and SediMeter™ reported motion was <0.5mm for nearly every measurement, but the range of elevation differences spanned from -1.0mm to +1.1mm.

When the data from all the tests performed on the three SediMeters™ were combined, the final test population was composed of 336 bed-level measurements. Due to this large test population size, it is acceptable to assume a normal distribution for the data (Rao 1998). Based on this assumption, the empirical rule can be utilized. That rule states that 95% and 99.7% of the measurements in a

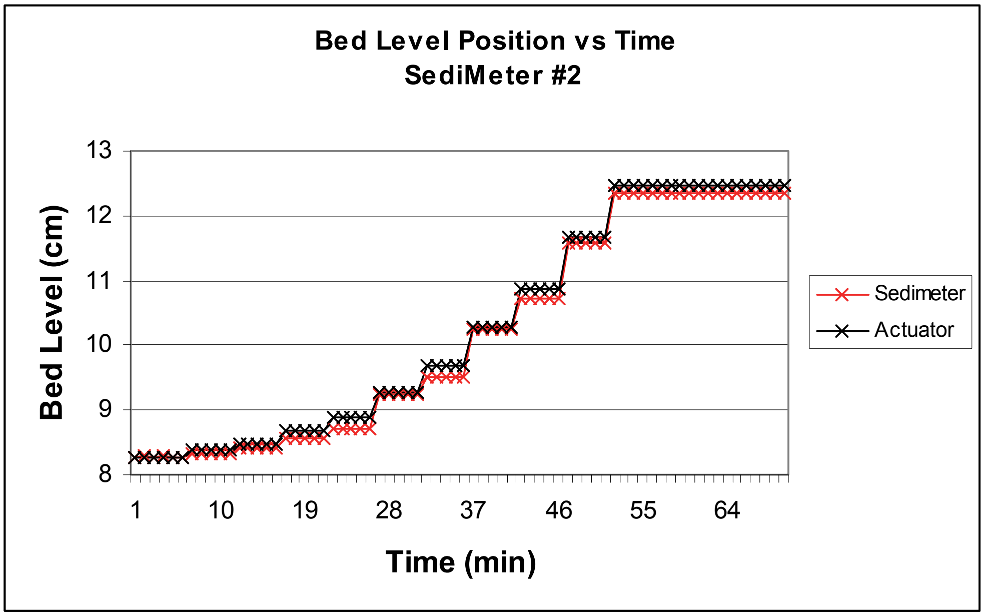

Figure 5. Graph showing the bed-level results of one test performed on SediMeter™ #2. The red line shows the level recorded by the SediMeter™ while the black line shows the motion of the actuator.

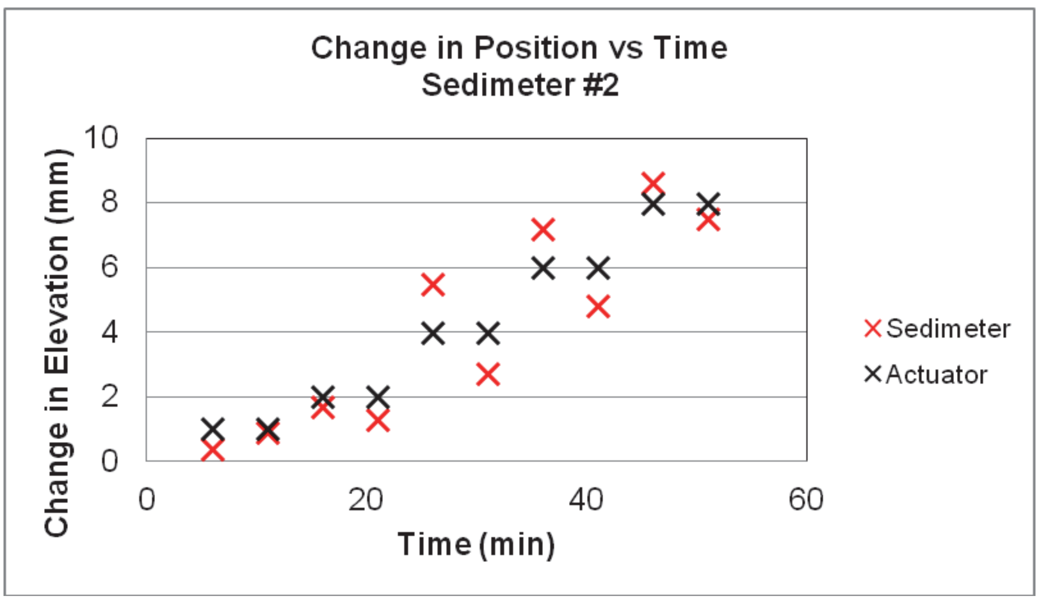

Figure 6. Graph showing the change in elevation recorded by SediMeter™ #2 compared to the change in elevation of the linear actuator. The SediMeter™ frequently shows periods of underestimation of actuator motion that are followed by overestimations of motion.

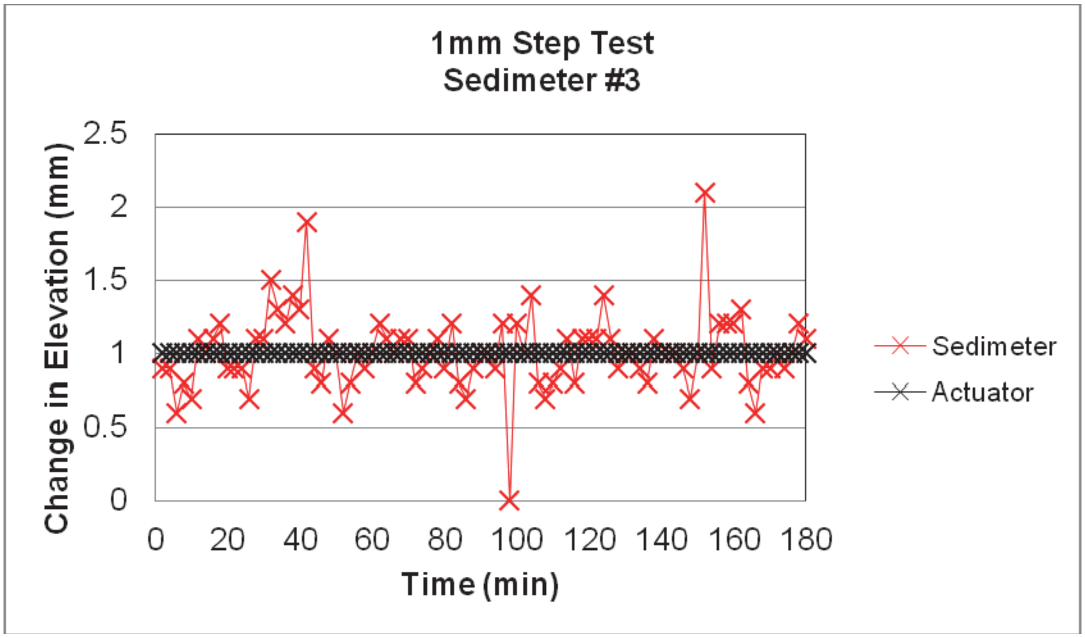

Figure 7. Graph showing the change in elevation recorded by SediMeter™ #3 compared to the change in elevation of the linear actuator. The actuator was moved at constant 1mm intervals throughout the duration of the test. The SediMeter™ showed near equal underestimations and overestimations of that motion (n=38 and 35, respectively).

population are within two and three standard deviations (σ) of the population mean, respectively. The average difference between SediMeter™ recorded motion and the motion of the actuator was found to be 0.0mm. This was due to the SediMeter's™ near equal over and underestimate of bed level. It was found that 35% of the measurements made by the instrument were overestimates of the actuator motion, 39% were underestimates, and 26% showed no difference between actuator and Sedimeter™ recorded motion. The calculated standard deviation of the differences was 0.84mm, which gave values of 1.7mm and 2.5mm for 2σ and 3σ, respectively. Therefore, the accuracy of the SediMeter's™ bed-level elevation measurements was determined to be ±1.7mm for 95% of measurements, or ±2.5mm for 99.7% of measurements.

CONCLUSIONS

Based on the experiments that were performed at ERDC-CHL, it was determined that the SediMeter™ is capable of accurately determining the bed level with a range of uncertainty between ±1.7mm to ±2.5mm for 95% or 99.7% certainty, respectively. This translates to a total uncertainty of 3.4-5.0mm for each measurement. While this range of error would be considered quite small for many applications, for the purpose of resolving sedimentation associated with dredge-induced plumes this range is quite large. It has been suggested that sedimentation on the scale of 1mm or less can have impacts upon sensitive habitats. If this is indeed true, then the SediMeter™ would be unlikely to accurately and reliably detect such small-scale sedimentation.

In addition to the SediMeter™ not being capable of resolving such fine-scale changes in bed-level elevation, the fact that the instrument must come directly in contact with the bed could result in scouring. While the small diameter of the SediMeter™ would help to reduce scour, other

environmental factors such as grain size, flow velocity, flow depth, and Froude number would also play a role in determining how much scour would result around the instrument (Khanbilvardi et al. 1988). In cases where resulting scour was on the same order of magnitude – or larger – as the desired measurement resolution, this scour would prevent the collection of meaningful bed-level data.

Though the SediMeter™ was not determined be an appropriate instrument for the measurement of bed-level changes that are on the order of 1mm or less, the instrument does provide stable and accurate measurements at the 1cm or greater scale. Therefore, in research and monitoring applications where bed-level changes are on the order of centimeters, the SediMeter™ could be a useful instrument. An example of one such application in the dredging industry would be to utilize multiple SediMeters™ to monitor land-building activities with dredged material placement. These instruments could track bed elevation changes as dredged material is pumped into an area such as a wetland. They could also be used to evaluate the geomorphic stability of marshes and islands after they were constructed. In dredging-related studies such as these, large-scale elevation changes that are on the order of several centimeters would be of importance and therefore would be more appropriate for the use of the SediMeter™.

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APPENDIX A

Test Data: SediMeter™ #1

Sedimeter™ #	Date & Time	Sedimeter™ Recorded Level (cm)	Level based on Actuator Motion (cm)	Sedimeter™ Recorded Motion (mm)	Actuator Motion (mm)	Difference (mm)
1	7/21/11 16:07	8.56	8.56	0	0	0
1	7/21/11 16:09	8.54	8.46	0.2	1	-0.8
1	7/21/11 16:11	8.49	8.36	0.5	1	-0.5
1	7/21/11 16:13	8.42	8.26	0.7	1	-0.3
1	7/21/11 16:15	8.33	8.16	0.9	1	-0.1
1	7/21/11 16:17	8.23	8.06	1	1	0
1	7/21/11 16:19	8.07	7.96	1.6	1	0.6
1	7/21/11 16:21	7.87	7.86	2	1	1
1	7/21/11 16:23	7.74	7.76	1.3	1	0.3
1	7/21/11 16:25	7.66	7.66	0.8	1	-0.2
1	7/21/11 16:27	7.6	7.56	0.6	1	-0.4
1	7/21/11 16:29	7.56	7.46	0.4	1	-0.6
1	7/21/11 16:31	7.51	7.36	0.5	1	-0.5
1	7/21/11 16:33	7.45	7.26	0.6	1	-0.4
1	7/21/11 16:35	7.35	7.16	1	1	0
1	7/21/11 16:37	7.26	7.06	0.9	1	-0.1
1	7/20/11 20:47	3	3	0	0	0
1	7/20/11 20:49	2.99	3	0.1	0	0.1
1	7/20/11 20:51	2.99	3	0	0	0
1	7/20/11 20:53	2.99	3	0	0	0
1	7/20/11 20:55	4	4	10.1	10	0.1
1	7/20/11 20:57	4.89	5	8.9	10	-1.1
1	7/20/11 20:59	5.61	6	7.2	10	-2.8
1	7/20/11 21:01	5.77	6	1.6	0	1.6
1	7/20/11 21:03	6.93	7	11.6	10	1.6
1	7/20/11 21:05	7.92	8	9.9	10	-0.1
1	7/8/11 16:15	32	32	0	0	0
1	7/8/11 16:18	32.04	32.025	0.4	0.25	0.15
1	7/8/11 16:21	32.03	32.025	0.1	0	0.1
1	7/8/11 16:24	32.09	32.05	0.6	0.25	0.35
1	7/8/11 16:27	32.15	32.075	0.6	0.25	0.35
1	7/8/11 16:30	32.2	32.1	0.5	0.25	0.25
1	7/8/11 16:33	32.22	32.125	0.2	0.25	-0.05
1	7/8/11 16:36	32.28	32.15	0.6	0.25	0.35
1	7/8/11 16:39	32.32	32.175	0.4	0.25	0.15
1	7/8/11 16:42	32.34	32.2	0.2	0.25	-0.05
1	7/8/11 16:45	32.34	32.2	0	0	0

APPENDIX B

Test Data: SediMeter™ #2

Sedimeter™ #	Date & Time	Sedimeter™ Recorded Level (cm)	Level based on Actuator Motion (cm)	Sedimeter™ Recorded Motion (mm)	Actuator Motion (mm)	Difference (mm)
2	7/21/11 20:56	1.22	1.22	0	0	0
2	7/21/11 20:58	1.32	1.32	1	1	0
2	7/21/11 21:00	1.4	1.42	0.8	1	-0.2
2	7/21/11 21:02	1.5	1.52	1	1	0
2	7/21/11 21:04	1.56	1.62	0.6	1	-0.4
2	7/21/11 21:06	1.61	1.72	0.5	1	-0.5
2	7/21/11 21:08	1.65	1.82	0.4	1	-0.6
2	7/21/11 21:10	1.72	1.92	0.7	1	-0.3
2	7/21/11 21:12	1.86	2.02	1.4	1	0.4
2	7/21/11 21:14	2.06	2.12	2	1	1
2	7/21/11 21:16	2.23	2.22	1.7	1	0.7
2	7/21/11 21:18	2.32	2.32	0.9	1	-0.1
2	7/21/11 21:20	2.41	2.42	0.9	1	-0.1
2	7/21/11 21:22	2.5	2.52	0.9	1	-0.1
2	7/21/11 21:24	2.52	2.62	0.2	1	-0.8
2	7/21/11 21:26	2.55	2.72	0.3	1	-0.7
2	7/21/11 20:22	8.56	8.56	0	0	0
2	7/21/11 20:24	7.56	7.56	10	10	0
2	7/21/11 20:26	6.53	6.56	10.3	10	0.3
2	7/21/11 20:28	5.55	5.56	9.8	10	-0.2
2	7/21/11 20:30	5.35	4.56	2	10	-8
2	7/21/11 20:32	4.38	3.56	9.7	10	-0.3
2	7/21/11 20:34	3.4	2.56	9.8	10	-0.2
2	7/21/11 20:36	2.41	1.56	9.9	10	-0.1
2	7/21/11 20:38	1.41	0.56	10	10	0
2	9/23/11 15:11	8.22	8.22	0	0	0
2	9/23/11 15:13	8.23	8.22	0.1	0	0.1
2	9/23/11 15:15	8.22	8.22	0.1	0	0.1
2	9/23/11 15:17	8.31	8.32	0.9	1	-0.1
2	9/23/11 15:19	8.31	8.32	0	0	0
2	9/23/11 15:21	8.34	8.42	0.3	1	-0.7
2	9/23/11 15:23	8.44	8.52	1	1	0
2	9/23/11 15:25	8.52	8.62	0.8	1	-0.2
2	9/23/11 15:27	8.6	8.72	0.8	1	-0.2
2	9/23/11 15:29	8.76	8.92	1.6	2	-0.4
2	9/23/11 15:31	9.06	9.12	3	2	1
2	9/23/11 15:33	9.28	9.32	2.2	2	0.2
2	9/23/11 15:35	9.39	9.52	1.1	2	-0.9
2	9/23/11 15:37	9.72	10.02	3.3	5	-1.7
2	9/23/11 15:39	10.37	10.52	6.5	5	1.5
2	9/23/11 15:41	10.91	11.02	5.4	5	0.4

Sedimeter™ #	Date & Time	Sedimeter™ Recorded Level (cm)	Level based on Actuator Motion (cm)	Sedimeter™ Recorded Motion (mm)	Actuator Motion (mm)	Difference (mm)
2	9/23/11 15:43	11.44	11.52	5.3	5	0.3
2	9/23/11 15:45	12.36	12.52	9.2	10	-0.8
2	9/23/11 15:47	13.43	13.62	10.7	11	-0.3
2	9/23/11 15:49	14.4	14.62	9.7	10	-0.3
2	9/23/11 15:51	14.4	14.62	0	0	0
2	9/23/11 15:53	15.38	15.62	9.8	10	-0.2
2	9/23/11 15:55	15.85	16.12	4.7	5	-0.3
2	9/23/11 15:57	16.46	16.62	6.1	5	1.1
2	9/23/11 15:59	16.96	17.12	5	5	0
2	9/23/11 16:01	17.21	17.32	2.5	2	0.5
2	9/23/11 16:03	17.34	17.52	1.3	2	-0.7
2	9/23/11 16:05	17.51	17.72	1.7	2	-0.3
2	9/23/11 16:07	17.62	17.82	1.1	1	0.1
2	9/23/11 16:09	17.62	17.82	0	0	0
2	9/23/11 16:11	17.71	17.92	0.9	1	-0.1
2	9/23/11 16:13	17.82	18.02	1.1	1	0.1
2	9/23/11 16:15	17.93	18.12	1.1	1	0.1
2	9/23/11 19:14	8.28	8.28	0	0	0
2	9/23/11 19:15	8.29	8.28	0.1	0	0.1
2	9/23/11 19:16	8.28	8.28	0.1	0	0.1
2	9/23/11 19:17	8.29	8.28	0.1	0	0.1
2	9/23/11 19:18	8.28	8.28	0.1	0	0.1
2	9/23/11 19:19	8.28	8.28	0	0	0
2	9/23/11 19:20	8.32	8.38	0.4	1	-0.6
2	9/23/11 19:21	8.32	8.38	0	0	0
2	9/23/11 19:22	8.32	8.38	0	0	0
2	9/23/11 19:23	8.32	8.38	0	0	0
2	9/23/11 19:24	8.32	8.38	0	0	0
2	9/23/11 19:25	8.41	8.48	0.9	1	-0.1
2	9/23/11 19:26	8.41	8.48	0	0	0
2	9/23/11 19:27	8.41	8.48	0	0	0
2	9/23/11 19:28	8.41	8.48	0	0	0
2	9/23/11 19:29	8.4	8.48	0.1	0	0.1
2	9/23/11 19:30	8.57	8.68	1.7	2	-0.3
2	9/23/11 19:31	8.57	8.68	0	0	0
2	9/23/11 19:32	8.57	8.68	0	0	0
2	9/23/11 19:33	8.57	8.68	0	0	0
2	9/23/11 19:34	8.57	8.68	0	0	0
2	9/23/11 19:35	8.7	8.88	1.3	2	-0.7
2	9/23/11 19:36	8.7	8.88	0	0	0
2	9/23/11 19:37	8.7	8.88	0	0	0
2	9/23/11 19:38	8.7	8.88	0	0	0
2	9/23/11 19:39	8.7	8.88	0	0	0
2	9/23/11 19:40	9.25	9.28	5.5	4	1.5

Sedimeter™ #	Date & Time	Sedimeter™ Recorded Level (cm)	Level based on Actuator Motion (cm)	Sedimeter™ Recorded Motion (mm)	Actuator Motion (mm)	Difference (mm)
2	9/23/11 19:41	9.25	9.28	0	0	0
2	9/23/11 19:42	9.25	9.28	0	0	0
2	9/23/11 19:43	9.25	9.28	0	0	0
2	9/23/11 19:44	9.25	9.28	0	0	0
2	9/23/11 19:45	9.52	9.68	2.7	4	-1.3
2	9/23/11 19:46	9.52	9.68	0	0	0
2	9/23/11 19:47	9.52	9.68	0	0	0
2	9/23/11 19:48	9.52	9.68	0	0	0
2	9/23/11 19:49	9.52	9.68	0	0	0
2	9/23/11 19:50	10.24	10.28	7.2	6	1.2
2	9/23/11 19:51	10.24	10.28	0	0	0
2	9/23/11 19:52	10.24	10.28	0	0	0
2	9/23/11 19:53	10.24	10.28	0	0	0
2	9/23/11 19:54	10.24	10.28	0	0	0
2	9/23/11 19:55	10.72	10.88	4.8	6	-1.2
2	9/23/11 19:56	10.72	10.88	0	0	0
2	9/23/11 19:57	10.72	10.88	0	0	0
2	9/23/11 19:58	10.72	10.88	0	0	0
2	9/23/11 19:59	10.72	10.88	0	0	0
2	9/23/11 20:00	11.58	11.68	8.6	8	0.6
2	9/23/11 20:01	11.58	11.68	0	0	0
2	9/23/11 20:02	11.59	11.68	0.1	0	0.1
2	9/23/11 20:03	11.58	11.68	0.1	0	0.1
2	9/23/11 20:04	11.59	11.68	0.1	0	0.1
2	9/23/11 20:05	12.34	12.48	7.5	8	-0.5
2	9/23/11 20:06	12.35	12.48	0.1	0	0.1
2	9/23/11 20:07	12.34	12.48	0.1	0	0.1
2	9/23/11 20:08	12.35	12.48	0.1	0	0.1
2	9/23/11 20:09	12.35	12.48	0	0	0
2	9/23/11 20:10	12.34	12.48	0.1	0	0.1
2	9/23/11 20:11	12.35	12.48	0.1	0	0.1
2	9/23/11 20:12	12.34	12.48	0.1	0	0.1
2	9/23/11 20:13	12.35	12.48	0.1	0	0.1
2	9/23/11 20:14	12.34	12.48	0.1	0	0.1
2	9/23/11 20:15	12.35	12.48	0.1	0	0.1
2	9/23/11 20:16	12.34	12.48	0.1	0	0.1
2	9/23/11 20:17	12.35	12.48	0.1	0	0.1
2	9/23/11 20:18	12.35	12.48	0	0	0
2	9/23/11 20:19	12.35	12.48	0	0	0
2	9/23/11 20:20	12.35	12.48	0	0	0
2	9/23/11 20:21	12.34	12.48	0.1	0	0.1
2	9/23/11 20:22	12.35	12.48	0.1	0	0.1
2	9/23/11 20:23	12.35	12.48	0	0	0
2	9/22/11 20:02			0	0	0

Sedimeter™ #	Date & Time	Sedimeter™ Recorded Level (cm)	Level based on Actuator Motion (cm)	Sedimeter™ Recorded Motion (mm)	Actuator Motion (mm)	Difference (mm)
2	9/22/11 20:04			0.1	0	0.1
2	9/22/11 20:06			0.8	1	-0.2
2	9/22/11 20:08			0.6	1	-0.4
2	9/22/11 20:10			1	1	0
2	9/22/11 20:12			0.7	1	-0.3
2	9/22/11 20:14			0.8	1	-0.2
2	9/22/11 20:16			0.6	1	-0.4
2	9/22/11 20:18			0.7	1	-0.3
2	9/22/11 20:20			1.6	1	0.6
2	9/22/11 20:22			1.8	1	0.8
2	9/22/11 20:24			1.3	1	0.3
2	9/22/11 20:26			0.7	1	-0.3
2	9/22/11 20:28			0.5	1	-0.5
2	9/22/11 20:30			0.8	1	-0.2
2	9/22/11 20:32			0.8	1	-0.2
2	9/22/11 20:34			0.5	1	-0.5
2	9/22/11 20:36			0.4	1	-0.6
2	9/22/11 20:38			0	0	0
2	9/22/11 20:40			0.6	1	-0.4
2	9/22/11 20:42			1.4	1	0.4
2	9/22/11 20:44			2.3	1	1.3
2	9/22/11 20:46			2	1	1
2	9/22/11 20:48			0.6	1	-0.4
2	9/21/11 15:12			0	0	0
2	9/21/11 15:14			0	0	0
2	9/21/11 15:16			3.7	5	-1.3
2	9/21/11 15:18			2.7	3	-0.3
2	9/21/11 15:20			1.9	1	0.9
2	9/21/11 15:22			1.5	1	0.5
2	9/21/11 15:24			0.7	1	-0.3
2	9/21/11 15:26			1.3	2	-0.7
2	9/21/11 15:28			2.2	4	-1.8
2	9/21/11 15:30			7.6	6	1.6
2	9/21/11 15:32			9.3	8	1.3
2	9/21/11 15:34			9.4	10	-0.6
2	9/21/11 15:36			10.5	11	-0.5
2	9/21/11 15:38			12.2	13	-0.8
2	9/21/11 15:40			16.3	15	1.3
2	9/21/11 15:42			6.3	7	-0.7
2	9/21/11 15:44			2.6	2	0.6
2	9/21/11 15:46			1.2	1	0.2
2	9/21/11 15:48			1	1	0
2	9/21/11 15:50			0.5	1	-0.5
2	9/21/11 18:45			0	0	0

Sedimeter™ #	Date & Time	Sedimeter™ Recorded Level (cm)	Level based on Actuator Motion (cm)	Sedimeter™ Recorded Motion (mm)	Actuator Motion (mm)	Difference (mm)
2	9/21/11 18:47			0	0	0
2	9/21/11 18:49			0.1	0	0.1
2	9/21/11 18:51			0	0	0
2	9/21/11 18:53			0.2	1	-0.8
2	9/21/11 18:55			0.3	1	-0.7
2	9/21/11 18:57			0.5	1	-0.5
2	9/21/11 18:59			2.8	1	1.8
2	9/21/11 19:01			5.9	1	4.9
2	9/21/11 19:03			0.1	2	-1.9
2	9/21/11 19:05			0	2	-2
2	9/21/11 19:07			0.3	2	-1.7
2	9/21/11 19:09			0.5	2	-1.5
2	9/21/11 19:11			5	2	3
2	9/21/11 19:13			3.7	4	-0.3
2	9/21/11 19:15			10.3	6	4.3
2	9/21/11 19:17			5	8	-3
2	9/21/11 19:19			9.5	10	-0.5
2	9/21/11 19:21			5.7	2	3.7
2	9/21/11 19:23			0	0	0
2	9/21/11 19:25			1.6	4	-2.4
2	9/21/11 19:27			0.5	1	-0.5
2	9/21/11 19:29			0.4	1	-0.6
2	9/21/11 19:31			0.4	1	-0.6
2	9/21/11 19:33			0	0	0

APPENDIX C

Test Data: SediMeter™ #3

Sedimeter™ #	Date & Time	Sedimeter™ Recorded Level (cm)	Level based on Actuator Motion (cm)	Sedimeter™ Recorded Motion (mm)	Actuator Motion (mm)	Difference (mm)
3	7/22/11 16:16	14.22	14.22	0	0	0
3	7/22/11 16:18	14.13	14.12	0.9	1	-0.1
3	7/22/11 16:20	14.04	14.02	0.9	1	-0.1
3	7/22/11 16:22	13.98	13.92	0.6	1	-0.4
3	7/22/11 16:24	13.9	13.82	0.8	1	-0.2
3	7/22/11 16:26	13.83	13.72	0.7	1	-0.3
3	7/22/11 16:28	13.72	13.62	1.1	1	0.1
3	7/22/11 16:30	13.62	13.52	1	1	0
3	7/22/11 16:32	13.51	13.42	1.1	1	0.1
3	7/22/11 16:34	13.39	13.32	1.2	1	0.2
3	7/22/11 16:36	13.3	13.22	0.9	1	-0.1
3	7/22/11 16:38	13.21	13.12	0.9	1	-0.1
3	7/22/11 16:40	13.12	13.02	0.9	1	-0.1
3	7/22/11 16:42	13.05	12.92	0.7	1	-0.3
3	7/22/11 16:44	12.94	12.82	1.1	1	0.1
3	7/22/11 16:46	12.83	12.72	1.1	1	0.1
3	7/22/11 16:48	12.68	12.62	1.5	1	0.5
3	7/22/11 16:50	12.55	12.52	1.3	1	0.3
3	7/22/11 16:52	12.43	12.42	1.2	1	0.2
3	7/22/11 16:54	12.29	12.32	1.4	1	0.4
3	7/22/11 16:56	12.16	12.22	1.3	1	0.3
3	7/22/11 16:58	11.97	12.12	1.9	1	0.9
3	7/22/11 17:00	11.88	12.02	0.9	1	-0.1
3	7/22/11 17:02	11.8	11.92	0.8	1	-0.2
3	7/22/11 17:04	11.69	11.82	1.1	1	0.1
3	7/22/11 17:06	11.59	11.72	1	1	0
3	7/22/11 17:08	11.53	11.62	0.6	1	-0.4
3	7/22/11 17:10	11.45	11.52	0.8	1	-0.2
3	7/22/11 17:12	11.35	11.42	1	1	0
3	7/22/11 17:14	11.26	11.32	0.9	1	-0.1
3	7/22/11 17:16	11.16	11.22	1	1	0
3	7/22/11 17:18	11.04	11.12	1.2	1	0.2
3	7/22/11 17:20	10.93	11.02	1.1	1	0.1
3	7/22/11 17:22	10.83	10.92	1	1	0
3	7/22/11 17:24	10.72	10.82	1.1	1	0.1
3	7/22/11 17:26	10.61	10.72	1.1	1	0.1
3	7/22/11 17:28	10.53	10.62	0.8	1	-0.2
3	7/22/11 17:30	10.44	10.52	0.9	1	-0.1
3	7/22/11 17:32	10.34	10.42	1	1	0
3	7/22/11 17:34	10.23	10.32	1.1	1	0.1
3	7/22/11 17:36	10.14	10.22	0.9	1	-0.1

Sedimeter™ #	Date & Time	Sedimeter™ Recorded Level (cm)	Level based on Actuator Motion (cm)	Sedimeter™ Recorded Motion (mm)	Actuator Motion (mm)	Difference (mm)
3	7/22/11 17:38	10.02	10.12	1.2	1	0.2
3	7/22/11 17:40	9.94	10.02	0.8	1	-0.2
3	7/22/11 17:42	9.87	9.92	0.7	1	-0.3
3	7/22/11 17:44	9.78	9.82	0.9	1	-0.1
3	7/22/11 17:46	9.68	9.72	1	1	0
3	7/22/11 17:48	9.58	9.62	1	1	0
3	7/22/11 17:50	9.49	9.52	0.9	1	-0.1
3	7/22/11 17:52	9.37	9.42	1.2	1	0.2
3	7/22/11 17:54	9.37	9.32	0	1	-1
3	7/22/11 17:56	9.25	9.22	1.2	1	0.2
3	7/22/11 17:58	9.15	9.12	1	1	0
3	7/22/11 18:00	9.01	9.02	1.4	1	0.4
3	7/22/11 18:02	8.93	8.92	0.8	1	-0.2
3	7/22/11 18:04	8.86	8.82	0.7	1	-0.3
3	7/22/11 18:06	8.78	8.72	0.8	1	-0.2
3	7/22/11 18:08	8.69	8.62	0.9	1	-0.1
3	7/22/11 18:10	8.58	8.52	1.1	1	0.1
3	7/22/11 18:12	8.5	8.42	0.8	1	-0.2
3	7/22/11 18:14	8.39	8.32	1.1	1	0.1
3	7/22/11 18:16	8.28	8.22	1.1	1	0.1
3	7/22/11 18:18	8.17	8.12	1.1	1	0.1
3	7/22/11 18:20	8.03	8.02	1.4	1	0.4
3	7/22/11 18:22	7.92	7.92	1.1	1	0.1
3	7/22/11 18:24	7.83	7.82	0.9	1	-0.1
3	7/22/11 18:26	7.73	7.72	1	1	0
3	7/22/11 18:28	7.63	7.62	1	1	0
3	7/22/11 18:30	7.54	7.52	0.9	1	-0.1
3	7/22/11 18:32	7.46	7.42	0.8	1	-0.2
3	7/22/11 18:34	7.35	7.32	1.1	1	0.1
3	7/22/11 18:36	7.25	7.22	1	1	0
3	7/22/11 18:38	7.15	7.12	1	1	0
3	7/22/11 18:40	7.05	7.02	1	1	0
3	7/22/11 18:42	6.96	6.92	0.9	1	-0.1
3	7/22/11 18:44	6.89	6.82	0.7	1	-0.3
3	7/22/11 18:46	6.79	6.72	1	1	0
3	7/22/11 18:48	6.58	6.62	2.1	1	1.1
3	7/22/11 18:50	6.49	6.52	0.9	1	-0.1
3	7/22/11 18:52	6.37	6.42	1.2	1	0.2
3	7/22/11 18:54	6.25	6.32	1.2	1	0.2
3	7/22/11 18:56	6.13	6.22	1.2	1	0.2
3	7/22/11 18:58	6	6.12	1.3	1	0.3
3	7/22/11 19:00	5.92	6.02	0.8	1	-0.2
3	7/22/11 19:02	5.86	5.92	0.6	1	-0.4
3	7/22/11 19:04	5.77	5.82	0.9	1	-0.1

Sedimeter™ #	Date & Time	Sedimeter™ Recorded Level (cm)	Level based on Actuator Motion (cm)	Sedimeter™ Recorded Motion (mm)	Actuator Motion (mm)	Difference (mm)
3	7/22/11 19:06	5.68	5.72	0.9	1	-0.1
3	7/22/11 19:08	5.58	5.62	1	1	0
3	7/22/11 19:10	5.49	5.52	0.9	1	-0.1
3	7/22/11 19:12	5.39	5.42	1	1	0
3	7/22/11 19:14	5.27	5.32	1.2	1	0.2
3	7/22/11 19:16	5.16	5.22	1.1	1	0.1
3	7/22/11 15:44	14.23	14.23	0	0	0
3	7/22/11 15:46	13.36	13.23	8.7	10	-1.3
3	7/22/11 15:48	12.24	12.23	11.2	10	1.2
3	7/22/11 15:50	11.21	11.23	10.3	10	0.3
3	7/22/11 15:52	10.16	10.23	10.5	10	0.5
3	7/22/11 15:54	9.17	9.23	9.9	10	-0.1
3	7/22/11 15:56	8.21	8.23	9.6	10	-0.4
3	7/22/11 15:58	7.17	7.23	10.4	10	0.4
3	7/22/11 16:00	6.15	6.23	10.2	10	0.2
3	7/22/11 16:02	5.2	5.23	9.5	10	-0.5
3	7/22/11 16:04	4.18	4.23	10.2	10	0.2

APPENDIX D

Statistical Test Results

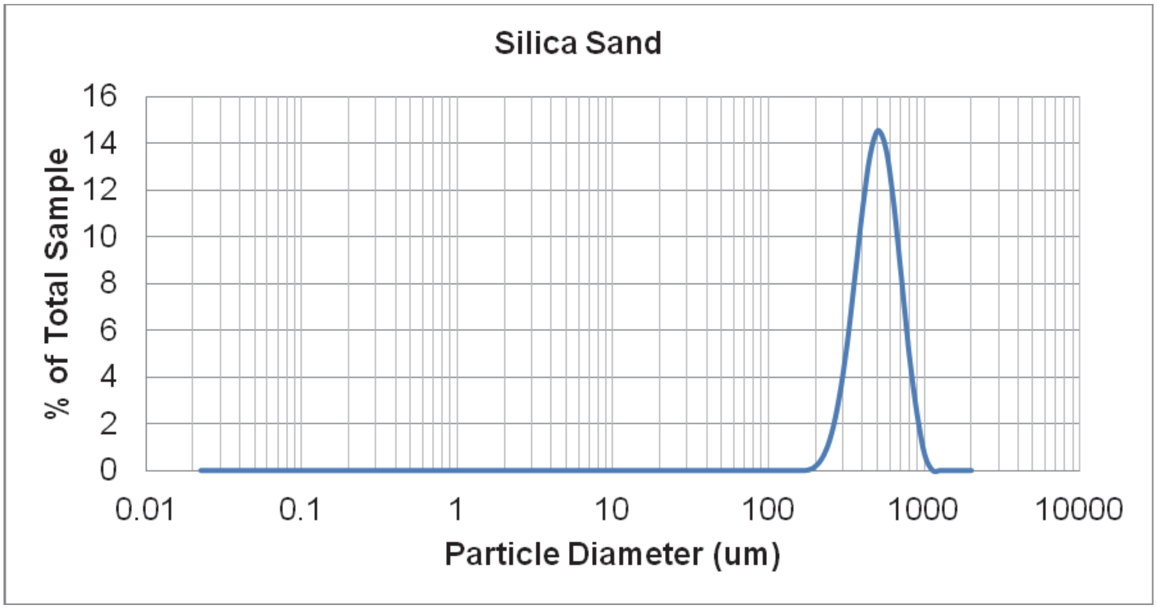
SediMeter™ #1 vs SediMeter™ #2 (α=0.05)		
t-Test: Two-Sample Assuming Equal Variances		
	Sed 1	*Sed 2*
Mean	**-0.02703**	**-0.06041**
Variance	0.502305	1.053016
Observations	37	197
Pooled Variance	0.967561	
Hypothesized Mean Difference	0	
Degrees of freedom	232	
t Stat	**0.189392**	
P(T<=t) one-tail	0.424976	
t Critical one-tail	1.651448	
P(T<=t) two-tail	0.849951	
t Critical two-tail	**1.970242**	
t-stat < t-critical, accept null hypothesis mean1=mean2		

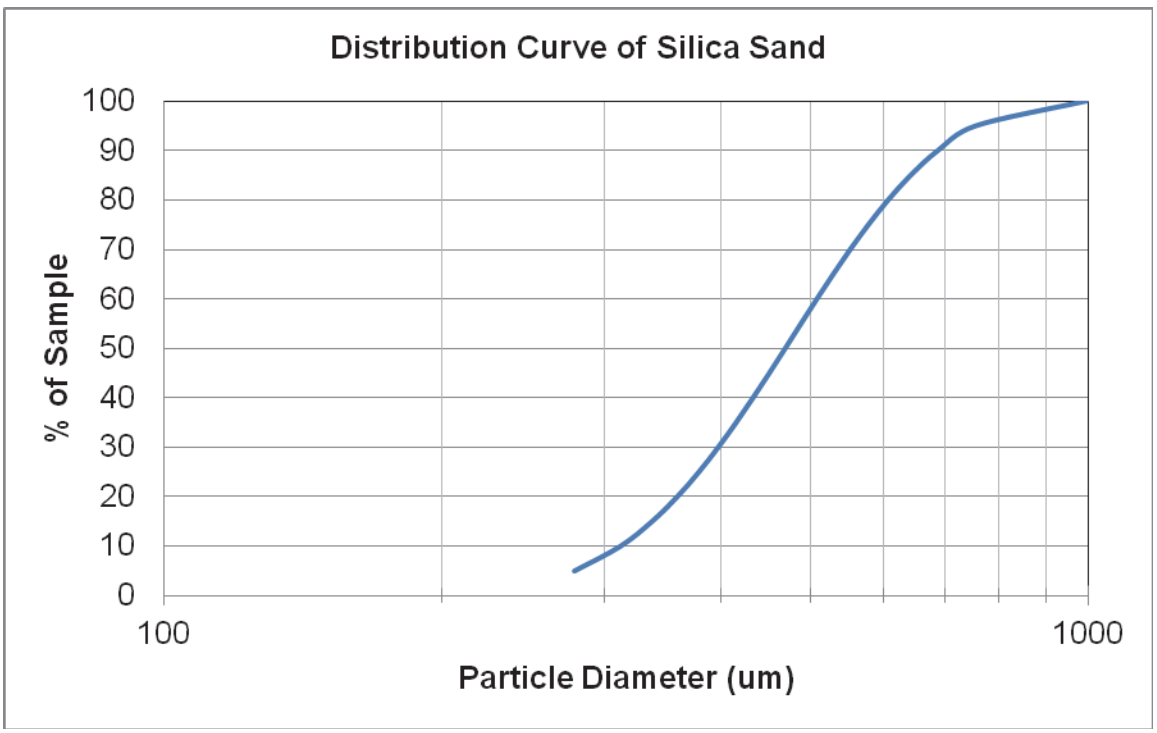
SediMeter™ #1 vs SediMeter™ #3 (α=0.05)		
t-Test: Two-Sample Assuming Equal Variances		
	Sed 1	*Sed 3*
Mean	**-0.02703**	**0.010784**
Variance	0.502305	0.10117
Observations	37	102
Pooled Variance	0.206577	
Hypothesized Mean Difference	0	
Degrees of freedom	137	
t Stat	**-0.43349**	
P(T<=t) one-tail	0.332672	
t Critical one-tail	1.656052	
P(T<=t) two-tail	0.665344	
t Critical two-tail	**1.977431**	
t-stat < t-critical, accept null hypothesis mean1=mean3		

SediMeter™ #2 vs SediMeter™ #3 (α=0.05)		
t-Test: Two-Sample Assuming Equal Variances		
	Sed 2	*Sed 3*
Mean	**-0.06041**	**0.010784**
Variance	1.053016	0.10117
Observations	197	102
Pooled Variance	0.729324	
Hypothesized Mean Difference	0	
Degrees of freedom	297	
t Stat	**-0.68337**	
P(T<=t) one-tail	0.247452	
t Critical one-tail	1.65	
P(T<=t) two-tail	0.494903	
t Critical two-tail	**1.967983**	
t-stat < t-critical, accept null hypothesis mean2=mean3		

APPENDIX E

Grain Size Data of Test Sand





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